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Neoclassical Diffusion and Dissipative Trapped-Electron Instabilities in the Transition from the Banana to Plateau Collisionality Regime*

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Abstract: A phenomenological procedure of separating velocity space into various regions of collisionality (banana, plateau, boundary layer), calculating the perturbed distribution functions accordingly, and appropriately averaging over velocity space, is used to analytically reproduce neoclassical diffusion and facilitate investigation of dissipative trapped-electron modes in this important transition regime.

Introduction: Of the various types of low frequency drift and trapped-particle instabilities [1], the most relevant mode in present tokamaks is the drift-dissipative trapped-electron instability. This mode has previously been derived only in the banana regime where the trapped-electrons are very collisionless. However, present experiments tend to operate in the transition ($\nu_* \sim 1$) between the banana ($\nu_* \ll 1$) and plateau ($1 \ll \nu_* \ll \epsilon^{-3/2}$) regimes. We investigate this transition region with a phenomenological model based upon separating velocity space into the various regimes of collisionality.

Partitioning of Velocity Space: Since the collision frequency and bounce time for a given particle are dependent on its kinetic energy, we can separate velocity space into Pfirsch-Schlüter, plateau and banana regimes, as shown in Figure 1. In the banana regime the effective collision frequency for trapped-particles [$\nu_{eff}(E) = \nu_{ei}(E)/\epsilon = 3\sqrt{2\pi}\,(T_e/2m_e)^{3/2}/2\epsilon\tau_{ei}$, in a Lorentz gas] is less than the trapped-particle bounce frequency [$\omega_b^T = \sqrt{2\epsilon E}/R_o q$], and hence this region is defined by $E > E_c \equiv 0.97\sqrt{\nu_*}\,T_e/m_e$, or $v > 0.985\,\nu_*^{1/4}\,v_T$, where $v_T = \sqrt{2T_e/m_e}$ is an electron thermal velocity, and ν_* is the ratio of effective collision frequency to bounce freque[ncy] for a thermal, trapped-electron. In the banana regime particles can be distinguished as trapped or untrapped according to their pitch-angles in velocity space. Between the trapped and untrapped regions, there is a collisional boundary layer in which the bounce time is longer than the time required for collisions to scatter particles out of this region. As we progress from the banana regime to lower energies in Fig. 1, we first encounter the plateau regime, and finally for sufficiently low energies ($v < 0.985\ \epsilon^{3/8} \nu_*^{1/4} v_T$) reach the very collisional Pfirsch-Schlüter regime.

Neoclassical Diffusion: As an example of the usefulness of this partitioning of velocity space, we calculate the neoclassical particle flux in equilibrium by solving for the distribution function in the various collisionality regimes and then appropriately adding up the various velocity space contributions to the particle flux integral $\Gamma = (m_e/2\pi|e|B_\theta) \int d\theta\ (1 + \epsilon \cos\theta) \int d^3v\, v_\parallel\, C_{ei}(f_e)$. For a Lorentz collision model and density gradient only, we obtain [2]

$$\Gamma = - K_{11}\, \epsilon^{1/2} \rho_{e\theta}^2\, n_e'/\tau_{ei}$$

where
$$\begin{aligned} K_{11} &= 0.73\, e^{-x_c} [1 - 0.89\sqrt{\nu_*}\, e^{x_c} E_1(x_c)] \\ &+ (\sqrt{2\pi}/8\nu_*)\ [e^{-y_c} (2 + 2y_c + y_c^2) - e^{-x_c} (2 + 2x_c + x_c^2)] \\ &+ \frac{\pi\epsilon^{3/2}}{32} \left[\frac{75}{16} \operatorname{erf}\sqrt{y_c} - e^{-y_c} \sqrt{\frac{y_c}{\pi}} \left(\frac{75}{8} + \frac{25}{4} y_c - \frac{3}{2} y_c^2\right)\right] \end{aligned}$$

in which $x_c = 0.97\sqrt{\nu_*}$, $y_c = \epsilon^{3/4} x_c$. We can recognize the first, second and third terms in square brackets in K_{11} as the contributions from the banana (including boundary layer), plateau and Pfirsch-Schlüter regimes, respectively. These analytic results compare quite favorably with the numerical formulae of Hazeltine and Hinton [3] (cf. Ref. 2). The reason why this separation of velocity space primarily by energy works so well is that energy scattering is weak in a neoclassical plasma; pitch-angle scattering is the dominant collisional process.

Dissipative Trapped-Electron Instabilities: For the temperature-gradient-driven version of these modes the dominant destabilizing contribution comes from the trapped-electrons in the banana regime -- region I in Fig. 1. Taking account of our separation of velocity space, we find that as ν_* increases this destabilizing integral does not change sign; however, it does decrease as $\exp(-\sqrt{\nu_*})$ for large ν_*. In the plateau region (II in Fig. 1) there is a collisional broadened Landau-type resonance, which, for $\omega \simeq \omega_*$ in the presence of a termperature gradient, has a stabilizing effect similar to that in collisionless drift modes [4]. The effective $k_\parallel$ here is $s/R_o q$, where s is an integer, and not $|\ell q-m|/R_o q \ll s/R_o q$ because for $\nu_* \sim 1$ the plasma is sufficiently collisional that the parallel variation of the potential seen by a particle is that seen within one bounce period and not the average seen over many bounce periods. Finally, there are contributions from the boundary layer between trapped and untrapped particles depending upon whether the wave frequency is larger (region III) or smaller (region IV) than the effective trapped particle collision frequency. The contribution from region IV is small because collisions simply further smear out the already small perturbed distribution function there. The contribution from region III, in which little diffusion takes place in the short period of the wave so that the diffusion is localized to the boundary layer, is similar to that calculated by Rosenbluth et.al. [5] for ions in the dissipative trapped-ion instability. Magnetic shear has a stabilizing effect on these modes that is found to be independent of the degree of collisionality. Stabilization of the temperature-gradient-driven version of the dissipative trapped electron instabilities occurs when ν_* becomes large enough so that the destabilizing contribution from region I becomes smaller than the stabilizing ones due to shear and the wave-particle resonance term. Specific numerical calculations of these effects are being performed.

References:

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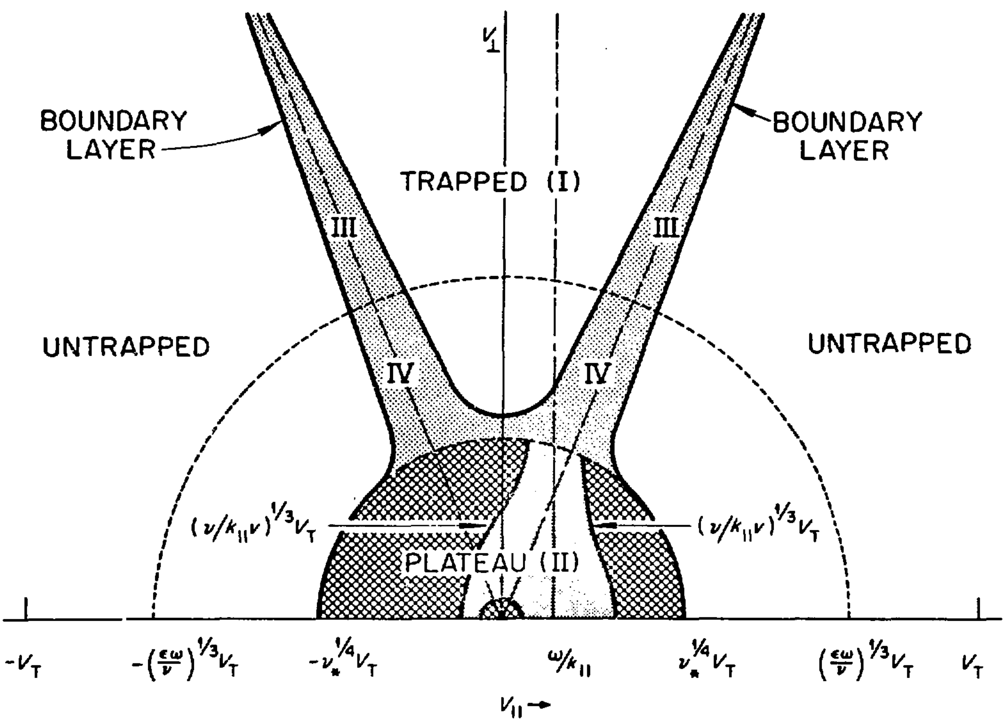

Figure 1 Regimes of collisionality in velocity space as seen on the outside of the torus.